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On the use of Quasi-orthogonal space-time-frequency codes in MB-OFDM UWB

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Abstract
Space-Time-Frequency Codes (STFCs), which haverecently been proposed in the literature for Multiband OFDMUltra-Wideband (MB-OFDM UWB) systems to improve thesystem capacity, error performance and wireless communicationrange, are all constructed based on orthogonal structures. Thispaper examines the application of Quasi-Orthogonal STFCs(QOSTFCs) to enhance further either data rate or error performancein the recently proposed STFC MB-OFDM UWB systems.It will be shown that QOSTFCs can provide significantly bettererror performance, compared to the conventional MB-OFDMUWB (without STFCs) as well as to the Orthogonal STFCs(OSTFCs) of the same order, at the same data rate, withoutincreasing the total transmission power. Equivalently, QOSTFCscan provide higher data rates with the same error performance,compared to OSTFCs.

Keywords
use, Quasi, orthogonal, space, time, frequency, codes, OFDM, UWB

Disciplines
Physical Sciences and Mathematics

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On the Use of Quasi-Orthogonal Space-Time-Frequency Codes in MB-OFDM UWB

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***Abstract*— Space-Time-Frequency Codes (STFCs), which have recently been proposed in the literature for Multiband OFDM Ultra-Wideband (MB-OFDM UWB) systems to improve the system capacity, error performance and wireless communication range, are all constructed based on orthogonal structures. This paper examines the application of Quasi-Orthogonal STFCs (QOSTFCs) to enhance further either data rate or error performance in the recently proposed STFC MB-OFDM UWB systems. It will be shown that QOSTFCs can provide significantly better error performance, compared to the conventional MB-OFDM UWB (without STFCs) as well as to the Orthogonal STFCs (OSTFCs) of the same order, at the same data rate, without increasing the total transmission power. Equivalently, QOSTFCs can provide higher data rates with the same error performance, compared to OSTFCs.** [1]

***Index Terms*— UWB, MB-OFDM, QOSTFC, STFC, MIMO.**

I. INTRODUCTION

Combination of the emerging technologies Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO), and Space-Time Codes (STCs) may provide a significant improvement in the maximum achievable wireless communications range, bit error performance, system capacity, and data rate. While the combination of OFDM, MIMO and STCs has been well examined in the literature [1], [2], [3], the combination of Multiband OFDM Ultra-Wideband (MB-OFDM UWB) communication, MIMO, and STCs has been almost unexplored with few published papers, such as [4], [5].

There are two main differences between channel characteristics in conventional OFDM systems and in MB-OFDM UWB ones. First, channels in the latter are much more dispersive than those in the former. Second, channel coefficients in the former are usually considered to be Rayleigh distributed, while those in the latter are log-normally distributed [6]. Furthermore, several technical specifications of conventional OFDM systems and MB-OFDM UWB ones are different. Therefore, the systems incorporating MB-OFDM UWB, MIMO, and STCs must be more specifically analyzed.

The incorporation of MB-OFDM UWB, MIMO and STCs has been somewhat mentioned in the literature. In particular, the combination of MB-OFDM UWB and Space-Time Block Codes (STBCs) has been mentioned in [4] for only 2 transmit antennas, i.e. the Alamouti code [7]. In [5], the authors proposed a general framework to analyze the performance of MB-OFDM MIMO UWB systems regardless of specific coding schemes in case of Nakagami frequency-selective fading channels. In [8] (see also [9]), we proposed the Space-Time-Frequency Coded MB-OFDM UWB (STFC MB-OFDM UWB) system for any number of transmit/reveive (Tx/Rx) antennas. We modified Tarokh's proof [10] to quantify the diversity and coding gains of the proposed STFC MB-OFDM UWB system in the log-normal distribution case [11]. We discovered that the maximum achievable diversity gain of the proposed STFC MB-OFDM UWB system is the product of the numbers of Tx and Rx antennas and the FFT size. We also derived the design criteria for STFCs in MB-OFDM UWB.

One disadvantage of STFCs constructed based directly on complex Orthogonal STBCs (OSTBCs) as mentioned in [8] is the reduced code rate when the number of Tx antennas increases. That is because OSTBCs for more than two Tx antennas cannot provide the full rate. To increase the code rate, in [12], the author proposed Quasi-Orthogonal STBCs (QOSTBCs) for four and eight Tx antennas providing higher data rates than the conventional OSTBCs of the same orders, while they still can provide a large (but not full) diversity. Equivalently, QOSTBCs can provide better error performance, compared to OSTBCs of the same order, at the same data rate [12].

The idea of QOSTBCs [12] can definitely be further extended to STFC MB-OFDM UWB systems. Therefore, in this paper, we consider the application of Quasi-Orthogonal STFCs (QOSTFCs), which have higher code rates than orthogonal STFCs (OSTFCs) of the same order, in the proposed STFC MB-OFDM UWB system. It will be shown that, although only partial diversity can be achieved, QOSTFCs may still provide better error performance over OSTFCs of the same order, without any increase of the total transmission power.

The paper is organized as follows. In Section II, we review briefly the specifications of STFC MB-OFDM systems mentioned in our previous paper [8]. Section III analyzes the feasibility of the deployment of QOSTFCs with the order up to 8 in the STFC MB-OFDM system, and analyzes the decoding metrics for an order-8 OSTFC and an order-8 QOSTFC as examples. In Section IV, simulation results are shown for the case of order-8 QOSTFCs to verify our analysis. Conclusions are drawn in Section V.

Notations: The following notations will be used throughout the paper. The superscripts $(.)^*$ and $(.)^T$ denote the complex

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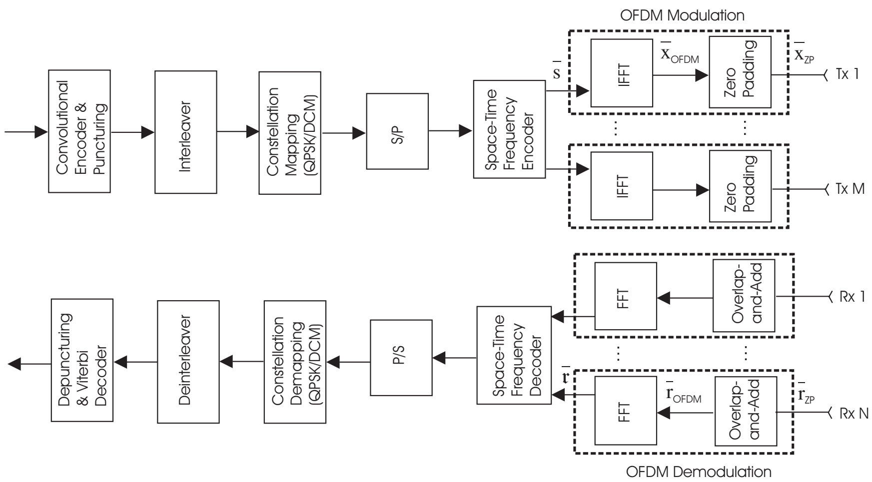

Fig. 1. Structural diagram of the proposed STFC MB-OFDM UWB systems.

conjugation and transposition operation, respectively. We denote $\bar{\mathbf{a}} \otimes \bar{\mathbf{b}}$, $\bar{\mathbf{a}} * \bar{\mathbf{b}}$, and $\bar{\mathbf{a}} \bullet \bar{\mathbf{b}}$ to be the linear convolution, the cyclic (or circular) convolution, and the element-wise (or Hadamard) product of the two vectors $\bar{\mathbf{a}}$ and $\bar{\mathbf{b}}$, respectively. Denote N_D and N_{fft} to be the number of data sub-carriers, and the FFT/IFFT size, respectively (for MB-OFDM UWB communications [13], $N_D = 100$ and $N_{fft} = 128$). Further, $\bar{\mathbf{a}}.\hat{\ } 2$ denotes the element-wise power-2 operation of $\bar{\mathbf{a}}$. The complex space $\mathcal{C}$ of a symbol s denotes all potential possibilities that the symbol s can take, while the N_D-dimensional complex space $\mathcal{C}^{N_D}$ of a length-N_D vector $\bar{\mathbf{s}}$ denotes all potential possibilities that the vector $\bar{\mathbf{s}}$ can take. We define $\bar{\mathbf{1}}$ as a column vector of length N_D, whose elements are all 1. Finally, $\| \, . \, \|_F$ denotes the Frobenius norm.

II. STFC MB-OFDM UWB System

The proposed STFC MB-OFDM UWB system [8] consisting of M Tx antennas and N Rx antennas, with the notations of signals at the considered reference points, is depicted in Fig. 1. The transmitted STFC is denoted as a matrix $\mathbf{S} = \{\bar{\mathbf{s}}_{t,m}\}_{T\times M}$, where T denotes the number of MB-OFDM symbol time slots required to transmit the whole STFC block. The code matrix $\mathbf{S}$ can be structured in the similar way as OSTBCs [7], [14], [15] or QOSTBCs [12] in conventional wireless STBC MIMO systems, except for that each element $\bar{\mathbf{s}}_{t,m}$ is not a complex number, but defined as a column vector $\bar{\mathbf{s}}_{t,m} = [s_{t,m,1}\ s_{t,m,2} \dots s_{t,m,N_{fft}}]^T$. The vectors $\bar{\mathbf{s}}_{t,m}$ are the original transmitted data before IFFT. The symbols $s_{t,m,k}$, for $k = 1, \dots, N_{fft}$, are drawn from a PSK, QAM, or Dual Carrier Modulation (DCM) [16] signal constellation.

Elements $\bar{\mathbf{s}}_{t,m}$ in each row of $\mathbf{S}$ are transmitted simultaneously through M Tx antennas in the same frequency band, while different rows of $\mathbf{S}$ might be transmitted in different frequency bands, following a certain Time-Frequency Code (TFC). Different TFCs (transmitted RF patterns) are described in more details in [13].

Denote $\mathcal{X} = \{\bar{\mathbf{x}}_{OFDM,t,m}\}_{T\times M}$ to be the matrix whose elements are the N_{fft}-point IFFTs of the respective elements in $\mathbf{S}$, then $\mathcal{X} = \{IFFT\{\bar{\mathbf{s}}_{t,m}\}\}_{T\times M} = \{\bar{\mathbf{x}}_{OFDM,t,m}\}_{T\times M}$. The symbols $\bar{\mathbf{x}}_{OFDM,t,m}$ are referred to as MB-OFDM symbols. Further, denote $\mathcal{X}_{\mathbf{ZP}} = \{\bar{\mathbf{x}}_{ZP,t,m}\}_{T\times M}$ to be the matrix whose elements are the respective elements in $\mathcal{X}$ appended by a Zero Padded Suffix (ZPS), which, according to [13], includes 37 zeros. Denote $\bar{\mathbf{h}}_{m,n} = [h_{m,n,1}\ \ h_{m,n,2} \dots h_{m,n,L_{m,n}}]^T$ to be the channel vector between the m-th Tx and n-th Rx antennas, for $m = 1, \dots, M, n = 1, \dots, N$, where the channel coefficients $h_{m,n,l}$ of the l-th path, $l = 1, \dots, L_{m,n}$, in this channel are modeled as independent *log-normally* distributed random variables (RVs). Let $L_{max} = \max\{L_{m,n}\}$, for $m = 1, \dots, M, n = 1, \dots, N$. Denote the MB-OFDM UWB channel coefficient matrix as $\mathbf{H} = \{\bar{\mathbf{h}}_{m,n,ZP}\}_{M\times N}$ where the vector $\bar{\mathbf{h}}_{m,n,ZP}$ is created from the corresponding channel vector $\bar{\mathbf{h}}_{m,n}$ by adding zeros to have the length L_{max}.

At the transmission of the t-th MB-OFDM symbol, the received signal at the n-th Rx antenna is calculated as

$$\bar{\mathbf{r}}_{ZP,t,n} = \sum_{m=1}^{M} \left(\bar{\mathbf{x}}_{ZP,t,m} \otimes \bar{\mathbf{h}}_{m,n}\right) + \bar{\mathbf{n}}_{t,n}. \qquad (1)$$

The elements of noise vector $\bar{\mathbf{n}}_{t,n}$ are considered to be independent complex Gaussian RVs.

We first theoretically assume that $L_{max} = (N_{ZPS} + 1)$, where N_{ZPS} denotes the length of the ZPS. In MB-OFDM system, a ZPS of a length $N_{ZPS} = 37$ [13] is appended to each symbol $\bar{\mathbf{x}}_{OFDM,t,m}$ at the transmitter to create a transmitted symbol $\bar{\mathbf{x}}_{ZP,t,m}$. At the receiver, an Overlap-And-Add Operation (OAAO) must be performed before FFT (i.e. N_{ZPS} samples of a received symbol $\bar{\mathbf{r}}_{ZP,t,n}$ from $(N_{fft}+1)$ to $(N_{fft}+N_{ZPS})$ are added to the beginning of that received symbol. Then the first N_{fft} samples of the resulting symbol will be used to decode the transmitted symbol). As a result, after performing OAAO for the received signal $\bar{\mathbf{r}}_{ZP,t,n}$ in (1) and then taking the first N_{fft} resulting samples, denoted as $\bar{\mathbf{r}}_{OFDM,t,n}$, the following equation is deduced

$$\bar{\mathbf{r}}_{OFDM,t,n} = \sum_{m=1}^{M} \bar{\mathbf{x}}_{OFDM,t,m} * \bar{\mathbf{h}}_{m,n} + \bar{\mathbf{n}}_{t,n}. \qquad (2)$$

For the circular convolution, we have the following property

$$\begin{aligned}\bar{\mathbf{x}}_{OFDM,t,m} * \bar{\mathbf{h}}_{m,n} &= IFFT\{FFT\{\bar{\mathbf{x}}_{OFDM,t,m}\} \bullet FFT\{\bar{\mathbf{h}}_{m,n}\}\} \\ &= IFFT\{\bar{\mathfrak{s}}_{t,m} \bullet \bar{\mathfrak{h}}_{m,n}\} \qquad (3)\end{aligned}$$

where $\bar{\mathfrak{h}}_{m,n}$ is the N_{fft}-point FFT of the channel vector $\bar{\mathbf{h}}_{m,n}$, i.e. $\bar{\mathfrak{h}}_{m,n} = FFT\{\bar{\mathbf{h}}_{m,n}\}$. We denote $\bar{\mathfrak{h}}_{m,n} = [\hbar_{m,n,1}\ \hbar_{m,n,2} \dots \hbar_{m,n,N_{fft}}]^T$.

After going through the FFT block at the receiver, the received signal becomes

$$FFT\{\bar{\mathbf{r}}_{OFDM,t,n}\} = \sum_{m=1}^{M} \bar{\mathfrak{s}}_{t,m} \bullet \bar{\mathfrak{h}}_{m,n} + FFT\{\bar{\mathbf{n}}_{t,n}\}. \quad (4)$$

Denote $\bar{\mathfrak{r}}_{t,n} = [\mathfrak{r}_{t,n,1}\quad \mathfrak{r}_{t,n,2} \dots \mathfrak{r}_{t,n,N_{fft}}]^T = FFT\{\bar{\mathbf{r}}_{OFDM,t,n}\}$ and $\bar{\mathfrak{n}}_{t,n} = [\mathfrak{n}_{t,n,1}\ \mathfrak{n}_{t,n,2} \dots \mathfrak{n}_{t,n,N_{fft}}]^T = FFT\{\bar{\mathbf{n}}_{t,n}\}$. Then (4) can be rewritten as follows

$$\bar{\mathfrak{r}}_{t,n} = \sum_{m=1}^{M} \bar{\mathfrak{s}}_{t,m} \bullet \bar{\mathfrak{h}}_{m,n} + \bar{\mathfrak{n}}_{t,n}. \quad (5)$$

Recall that $\bar{\mathfrak{s}}_{t,n}$ is the original modulated signal (before IFFT).

Denote $\mathcal{H} = \{\bar{\mathfrak{h}}_{m,n}\}_{M\times N}$ to be the matrix whose elements are the N_{fft}-point FFTs of the respective elements in the channel coefficient matrix $\mathbf{H}$. Further, denote $\mathbf{R} = \{\bar{\mathbf{r}}_{OFDM,t,n}\}_{T\times N}$ to be the received signal matrix, $\mathcal{R} = \{\bar{\mathfrak{r}}_{t,n}\}_{T\times N}$ to be the received signal matrix after FFT, and $\mathcal{N} = \{\bar{\mathfrak{n}}_{t,n}\}_{T\times N}$ to be the noise matrix. We can rewrite (5) in matrix form as follows

$$\mathcal{R} = \mathbf{S} \circ \mathcal{H} + \mathcal{N} \quad (6)$$

where we define the multiplication operation $\circ$ between $\mathbf{S}$ and $\mathcal{H}$ such that the (t, n)-th element of the resulting matrix is a N_{fft}-length column vector $\sum_{m=1}^{M} \bar{\mathfrak{s}}_{t,m} \bullet \bar{\mathfrak{h}}_{m,n}$.

From (6), we can realize that there exists a similarity between the mathematical model of the STFC MB-OFDM UWB system and that of the conventional wireless STC MIMO system [7], [14], [17]. The only difference between the two mathematical models is that elements in each matrix are numbers in the conventional STC MIMO system, while they are N_{fft}-length column vectors in the STFC MB-OFDM UWB system.

In fact, the multipath lengths are very likely to exceed the length of ZPS. This is especially true in MB-OFDM UWB systems where the average number of multipaths $\bar{N}_p$ is usually much bigger than $N_{ZPS} = 37$ (see Table I). Thus the transition from (1) to (5) as mentioned above is now an approximation only, because the circular convolution in (3) is approximately, but not exactly equal to the first N_{fft} samples achieved by the OAAO of the linear convolution $\bar{\mathbf{x}}_{ZP,t,m} \otimes \bar{\mathbf{h}}_{m,n}$ in (1). The energy of multipath components within the ZPS window will be captured, while the multipath components outside this window may be considered as interferences for the received signals. Eq. (1) represents the real received signals at the Rx antennas, while (5) shows the realistic concept used at the STFC decoder to decode the original transmitted signals. Therefore, to simulate the realistic performance of the proposed system, the signals received at the Rx antennas should be calculated from (1) with the linear convolution between the transmitted MB-OFDM symbols and the fully long multipath channels, while the decoding algorithm should be carried out based on (5), i.e. based on the circular convolution.

TABLE I

NUMBERS OF MULTIPATHS Np_{10dB}, $Np_{85\%}$, AND $\bar{N}_p$ [6].

	CM 1	CM 2	CM 3	CM 4
Np_{10dB}	12.5	15.3	24.9	41.2
$Np_{85\%}$	20.8	33.9	64.7	123.3
$\bar{N}_p$	287.9	739.5	1463.7	3905.5

Because the vector elements in $\mathbf{S}$ will be transformed via the IFFT operation to generate MB-OFDM symbols with N_{fft} subcarriers, we refer $\mathbf{S}$ to as a Space-Time-Frequency Code.

III. QUASI-ORTHOGONAL STFCS

If the code rate of a STFC is defined as the ratio of the number of transmitted MB-OFDM symbols and the number of time slots required to transmit the whole block of the code, it is well known that the Alamouti code [7] can provide a full rate for two Tx antennas,

$$\mathbf{S_2} = \begin{bmatrix} \bar{\mathfrak{s}}_1 & \bar{\mathfrak{s}}_2 \\ -\bar{\mathfrak{s}}_2^* & \bar{\mathfrak{s}}_1^* \end{bmatrix} \quad (7)$$

while higher-order codes for more than two Tx antennas cannot provide the full rate. However, they can still provide a higher diversity order than the Alamouti STFC. As a result, the higher-order codes can provide better error performance without any increase of the total transmission power. Higher order codes also provide potentially higher capacity for the wireless system. We note that, while high order codes (order 8 or greater) do not bring about a significant increase of the system capacity in the case $N = 1$ Rx antenna [14], they may significantly increase the system capacity in the case $N \geq 2$ Rx antennas. Therefore, the implementation of higher-order STFCs for multiple Tx/Rx antennas in STFC MB-OFDM UWB communications is still of our interest.

A question that could be raised is: what is the possible maximum order of STFCs which may be practically applied to MB-OFDM UWB systems? It is well known that Tx antennas should be separated from one another by at least $\lambda/2$, where λ is the UWB wavelength, in order to avoid the spatial correlation between the Tx antennas. For the UWB frequency range 3.1-10.6 GHz, this minimum distance is in the range of 14.2-48.4 mm. Let us consider the implementation of order-8 STFCs (8 Tx antennas are required). The length of UWB devices locating 8 Tx antennas should be about $7\lambda/2$, i.e. in the range 9.9-33.9 cm. This length is the typical length of wireless devices, such as wireless access points or routers. For more than 8 Tx antennas, the physical size of UWB devices might be too large and thus unpractical. Therefore, it can be stated that the application of up to 8 Tx antennas can be feasible in STFC MB-OFDM UWB communications.

As mentioned previously in Section I, QOSTFCs can be used to improve either the data rate or the error performance of MB-OFDM UWB systems. In particular, for 4 Tx antennas, the following full rate QOSTFC S_{4b}, which is constructed in

TABLE II

DECODING METRICS FOR $\mathbf{S_{8a}}$ WITH PSK OR QAM MODULATIONS.

Symbol	Decoding Metric
$\bar{\mathbf{s}}_1$	$\arg\min_{\bar{\mathbf{s}}\in\mathcal{C}^{N_D}} \Vert [\vert \sum_{n=1}^{N} (\bar{\mathfrak{h}}_{5,n} \bullet \bar{\mathfrak{r}}^*_{5,n} + \bar{\mathfrak{h}}_{2,n} \bullet \bar{\mathfrak{r}}^*_{2,n} + \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{1,n} + \bar{\mathfrak{h}}^*_{4,n} \bullet \bar{\mathfrak{r}}_{4,n} + \bar{\mathfrak{h}}_{3,n} \bullet \bar{\mathfrak{r}}^*_{3,n} + \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{8,n} + \bar{\mathfrak{h}}^*_{6,n} \bullet \bar{\mathfrak{r}}_{6,n} + \bar{\mathfrak{h}}^*_{7,n} \bullet \bar{\mathfrak{r}}_{7,n}) - \bar{\mathbf{s}}\vert .\hat{}2 + (-\bar{\mathbf{1}} + \sum_{m=1}^{8}\sum_{n=1}^{N} \vert\bar{\mathfrak{h}}_{m,n}\vert .\hat{}2) \bullet (\vert\bar{\mathbf{s}}\vert .\hat{}2)] \Vert_F^2$
$\bar{\mathbf{s}}_2$	$\arg\min_{\bar{\mathbf{s}}\in\mathcal{C}^{N_D}} \Vert [\vert \sum_{n=1}^{N} (- \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{7,n} - \bar{\mathfrak{h}}_{2,n} \bullet \bar{\mathfrak{r}}^*_{1,n} - \bar{\mathfrak{h}}_{6,n} \bullet \bar{\mathfrak{r}}^*_{5,n} + \bar{\mathfrak{h}}^*_{5,n} \bullet \bar{\mathfrak{r}}_{6,n} + \bar{\mathfrak{h}}^*_{7,n} \bullet \bar{\mathfrak{r}}_{8,n} + \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{2,n} + \bar{\mathfrak{h}}^*_{3} \bullet \bar{\mathfrak{r}}_{4} - \bar{\mathfrak{h}}_{4} \bullet \bar{\mathfrak{r}}^*_{3}) - \bar{\mathbf{s}}\vert .\hat{}2 + (-\bar{\mathbf{1}} + \sum_{m=1}^{8}\sum_{n=1}^{N} \vert\bar{\mathfrak{h}}_{m,n}\vert .\hat{}2) \bullet (\vert\bar{\mathbf{s}}\vert .\hat{}2)] \Vert_F^2$
$\bar{\mathbf{s}}_3$	$\arg\min_{\bar{\mathbf{s}}\in\mathcal{C}^{N_D}} \Vert [\vert \sum_{n=1}^{N} (\bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{6,n} - \bar{\mathfrak{h}}_{3,n} \bullet \bar{\mathfrak{r}}^*_{1,n} + \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{3,n} - \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{r}}_{4,n} + \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{r}}^*_{2,n} - \bar{\mathfrak{h}}_{7,n} \bullet \bar{\mathfrak{r}}^*_{5,n} + \bar{\mathfrak{h}}^*_{5,n} \bullet \bar{\mathfrak{r}}_{7,n} - \bar{\mathfrak{h}}^*_{6,n} \bullet \bar{\mathfrak{r}}_{8,n}) - \bar{\mathbf{s}}\vert .\hat{}2 + (-\bar{\mathbf{1}} + \sum_{m=1}^{8}\sum_{n=1}^{N} \vert\bar{\mathfrak{h}}_{m,n}\vert .\hat{}2) \bullet (\vert\bar{\mathbf{s}}\vert .\hat{}2)] \Vert_F^2$
$\bar{\mathbf{s}}_4$	$\arg\min_{\bar{\mathbf{s}}\in\mathcal{C}^{N_D}} \Vert [\vert \sum_{n=1}^{N} (- \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{4,n} + \bar{\mathfrak{h}}_{7,n} \bullet \bar{\mathfrak{r}}^*_{3,n} - \bar{\mathfrak{h}}_{5,n} \bullet \bar{\mathfrak{r}}^*_{1,n} + \bar{\mathfrak{h}}_{6,n} \bullet \bar{\mathfrak{r}}^*_{2,n} + \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{5,n} - \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{r}}_{6,n} - \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{r}}_{7,n} + \bar{\mathfrak{h}}^*_{4,n} \bullet \bar{\mathfrak{r}}_{8,n}) - \bar{\mathbf{s}}\vert .\hat{}2 + (-\bar{\mathbf{1}} + \sum_{m=1}^{8}\sum_{n=1}^{N} \vert\bar{\mathfrak{h}}_{m,n}\vert .\hat{}2) \bullet (\vert\bar{\mathbf{s}}\vert .\hat{}2)] \Vert_F^2$

the similar way as the QOSTBC proposed in [12], can be applied

$$\mathbf{S_{4b}} = \begin{bmatrix} \bar{\mathbf{s}}_1 & \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_3 & \bar{\mathbf{s}}_4 \\ -\bar{\mathbf{s}}_2^* & \bar{\mathbf{s}}_1^* & -\bar{\mathbf{s}}_4^* & \bar{\mathbf{s}}_3^* \\ -\bar{\mathbf{s}}_3^* & -\bar{\mathbf{s}}_4^* & \bar{\mathbf{s}}_1^* & \bar{\mathbf{s}}_2^* \\ \bar{\mathbf{s}}_4 & -\bar{\mathbf{s}}_3 & -\bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_1 \end{bmatrix}. \tag{8}$$

This QOSTFC provides a higher code rate with the penalty of loosing half diversity order, compared to the rate-3/4 OSTFC S_{4a}, which is constructed base on the code proposed in [18] for conventional wireless MIMO STBC systems

$$\mathbf{S_{4a}} = \begin{bmatrix} \bar{\mathbf{s}}_1 & \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_3 & 0 \\ -\bar{\mathbf{s}}_2^* & \bar{\mathbf{s}}_1^* & 0 & \bar{\mathbf{s}}_3 \\ -\bar{\mathbf{s}}_3^* & 0 & \bar{\mathbf{s}}_1^* & -\bar{\mathbf{s}}_2 \\ 0 & -\bar{\mathbf{s}}_3^* & \bar{\mathbf{s}}_2^* & \bar{\mathbf{s}}_1 \end{bmatrix}. \tag{9}$$

For 8 Tx antennas, the following rate-3/4 QOSTFC S_{8b} (constructed in the similar way as the QOSTBC proposed in [12]) can be used

$$\mathbf{S_{8b}} = \begin{bmatrix} \bar{\mathbf{s}}_1 & \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_3 & 0 & \bar{\mathbf{s}}_4 & \bar{\mathbf{s}}_5 & \bar{\mathbf{s}}_6 & 0 \\ -\bar{\mathbf{s}}_2^* & \bar{\mathbf{s}}_1^* & 0 & -\bar{\mathbf{s}}_3 & \bar{\mathbf{s}}_5^* & -\bar{\mathbf{s}}_4^* & 0 & \bar{\mathbf{s}}_6 \\ \bar{\mathbf{s}}_3^* & 0 & -\bar{\mathbf{s}}_1^* & -\bar{\mathbf{s}}_2 & -\bar{\mathbf{s}}_6^* & 0 & \bar{\mathbf{s}}_4^* & \bar{\mathbf{s}}_5 \\ 0 & -\bar{\mathbf{s}}_3^* & \bar{\mathbf{s}}_2^* & -\bar{\mathbf{s}}_1 & 0 & \bar{\mathbf{s}}_6^* & -\bar{\mathbf{s}}_5^* & \bar{\mathbf{s}}_4 \\ -\bar{\mathbf{s}}_4 & -\bar{\mathbf{s}}_5 & -\bar{\mathbf{s}}_6 & 0 & \bar{\mathbf{s}}_1 & \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_3 & 0 \\ -\bar{\mathbf{s}}_5^* & \bar{\mathbf{s}}_4^* & 0 & \bar{\mathbf{s}}_6 & -\bar{\mathbf{s}}_2^* & \bar{\mathbf{s}}_1^* & 0 & \bar{\mathbf{s}}_3 \\ \bar{\mathbf{s}}_6^* & 0 & -\bar{\mathbf{s}}_4^* & \bar{\mathbf{s}}_5 & \bar{\mathbf{s}}_3^* & 0 & -\bar{\mathbf{s}}_1^* & \bar{\mathbf{s}}_2 \\ 0 & \bar{\mathbf{s}}_6^* & -\bar{\mathbf{s}}_5^* & -\bar{\mathbf{s}}_4 & 0 & \bar{\mathbf{s}}_3^* & -\bar{\mathbf{s}}_2^* & -\bar{\mathbf{s}}_1 \end{bmatrix} \tag{10}$$

This QOSTFC provides a higher code rate with the penalty of loosing a portion of maximum diversity order, compared to the following rate-1/2 OSTFC S_{8a}, which is constructed based on the code proposed in [18] for conventional wireless STBC MIMO systems

$$\mathbf{S_{8a}} = \begin{bmatrix} \bar{\mathbf{s}}_1 & -\bar{\mathbf{s}}_2^* & -\bar{\mathbf{s}}_3^* & 0 & -\bar{\mathbf{s}}_4^* & 0 & 0 & 0 \\ \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_1^* & 0 & \bar{\mathbf{s}}_3^* & 0 & \bar{\mathbf{s}}_4^* & 0 & 0 \\ \bar{\mathbf{s}}_3 & 0 & \bar{\mathbf{s}}_1^* & -\bar{\mathbf{s}}_2^* & 0 & 0 & \bar{\mathbf{s}}_4^* & 0 \\ 0 & -\bar{\mathbf{s}}_3 & \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_1 & 0 & 0 & 0 & -\bar{\mathbf{s}}_4^* \\ \bar{\mathbf{s}}_4 & 0 & 0 & 0 & \bar{\mathbf{s}}_1^* & -\bar{\mathbf{s}}_2^* & -\bar{\mathbf{s}}_3^* & 0 \\ 0 & -\bar{\mathbf{s}}_4 & 0 & 0 & \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_1 & 0 & \bar{\mathbf{s}}_3^* \\ 0 & 0 & -\bar{\mathbf{s}}_4 & 0 & \bar{\mathbf{s}}_3 & 0 & \bar{\mathbf{s}}_1 & -\bar{\mathbf{s}}_2^* \\ 0 & 0 & 0 & \bar{\mathbf{s}}_4 & 0 & -\bar{\mathbf{s}}_3 & \bar{\mathbf{s}}_2 & \bar{\mathbf{s}}_1^* \end{bmatrix} \tag{11}$$

TABLE III

DECODING METRICS FOR $\mathbf{S_{8b}}$ WITH PSK OR QAM MODULATIONS.

Symbols	Decoding Metric
$(\bar{\mathbf{s}}_1, \bar{\mathbf{s}}_4)$	$\arg\min_{\bar{\mathbf{s}}_1,\bar{\mathbf{s}}_4\in\mathcal{C}^{N_D}} \Vert (\sum_{m=1}^{8}\sum_{n=1}^{N} \vert\bar{\mathfrak{h}}_{m,n}\vert .\hat{}2) \bullet (\vert\bar{\mathbf{s}}_1\vert .\hat{}2 + \vert\bar{\mathbf{s}}_4\vert .\hat{}2) + 2Real[\sum_{n=1}^{N}(-\bar{\mathfrak{h}}^*_{6,n} \bullet \bar{\mathfrak{r}}_{6,n} + \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{r}}^*_{4,n} + \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{r}}_{3,n} - \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{r}}_{2,n} + \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{8,n} - \bar{\mathfrak{h}}_{1,n} \bullet \bar{\mathfrak{r}}^*_{1,n} - \bar{\mathfrak{h}}_{5,n} \bullet \bar{\mathfrak{r}}^*_{5,n} + \bar{\mathfrak{h}}^*_{7,n} \bullet \bar{\mathfrak{r}}_{7,n}) \bullet \bar{\mathbf{s}}_1] + 2Real[\sum_{n=1}^{N}(\bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{r}}^*_{8,n} + \bar{\mathfrak{h}}^*_{6,n} \bullet \bar{\mathfrak{r}}_{2,n} + \bar{\mathfrak{h}}_{1,n} \bullet \bar{\mathfrak{r}}^*_{5,n} + \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{r}}_{7,n} - \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{r}}_{6,n} - \bar{\mathfrak{h}}^*_{7,n} \bullet \bar{\mathfrak{r}}_{3,n} - \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{4,n} - \bar{\mathfrak{h}}_{5,n} \bullet \bar{\mathfrak{r}}^*_{1,n}) \bullet \bar{\mathbf{s}}_4] + 2Real[\sum_{n=1}^{N}(-\bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{h}}_{5,n} - \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{h}}^*_{8,n} + \bar{\mathfrak{h}}^*_{4,n} \bullet \bar{\mathfrak{h}}_{8,n} - \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{h}}_{6,n} + \bar{\mathfrak{h}}_{1,n} \bullet \bar{\mathfrak{h}}^*_{5,n} - \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{h}}_{7,n} + \bar{\mathfrak{h}}_{2,n} \bullet \bar{\mathfrak{h}}^*_{6,n} + \bar{\mathfrak{h}}_{3,n} \bullet \bar{\mathfrak{h}}^*_{7,n}) \bullet \bar{\mathbf{s}}_1 \bullet \bar{\mathbf{s}}^*_4] \Vert_F^2$
$(\bar{\mathbf{s}}_2, \bar{\mathbf{s}}_5)$	$\arg\min_{\bar{\mathbf{s}}_2,\bar{\mathbf{s}}_5\in\mathcal{C}^{N_D}} \Vert (\sum_{m=1}^{8}\sum_{n=1}^{N} \vert\bar{\mathfrak{h}}_{m,n}\vert .\hat{}2) \bullet (\vert\bar{\mathbf{s}}_2\vert .\hat{}2 + \vert\bar{\mathbf{s}}_5\vert .\hat{}2) + 2Real[\sum_{n=1}^{N}(\bar{\mathfrak{h}}^*_{5,n} \bullet \bar{\mathfrak{r}}_{6,n} - \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{r}}_{4,n} + \bar{\mathfrak{h}}^*_{7,n} \bullet \bar{\mathfrak{r}}_{8,n} + \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{2,n} - \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{7,n} - \bar{\mathfrak{h}}_{6,n} \bullet \bar{\mathfrak{r}}^*_{5,n} - \bar{\mathfrak{h}}_{2,n} \bullet \bar{\mathfrak{r}}^*_{1,n} + \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{r}}^*_{3,n}) \bullet \bar{\mathbf{s}}_2] + 2Real[\sum_{n=1}^{N}(\bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{6,n} + \bar{\mathfrak{h}}_{2,n} \bullet \bar{\mathfrak{r}}^*_{5,n} - \bar{\mathfrak{h}}^*_{5,n} \bullet \bar{\mathfrak{r}}_{2,n} - \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{r}}^*_{7,n} + \bar{\mathfrak{h}}^*_{7,n} \bullet \bar{\mathfrak{r}}_{4,n} + \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{r}}_{8,n} - \bar{\mathfrak{h}}_{6,n} \bullet \bar{\mathfrak{r}}^*_{1,n} - \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{3,n}) \bullet \bar{\mathbf{s}}_5] + 2Real[\sum_{n=1}^{N}(-\bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{h}}_{6,n} + \bar{\mathfrak{h}}_{1,n} \bullet \bar{\mathfrak{h}}^*_{5,n} + \bar{\mathfrak{h}}_{3,n} \bullet \bar{\mathfrak{h}}^*_{7,n} - \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{h}}_{7,n} + \bar{\mathfrak{h}}^*_{4,n} \bullet \bar{\mathfrak{h}}_{8,n} - \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{h}}^*_{8,n} + \bar{\mathfrak{h}}_{2,n} \bullet \bar{\mathfrak{h}}^*_{6,n} - \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{h}}_{5,n}) \bullet \bar{\mathbf{s}}_2 \bullet \bar{\mathbf{s}}^*_5] \Vert_F^2$
$(\bar{\mathbf{s}}_3, \bar{\mathbf{s}}_6)$	$\arg\min_{\bar{\mathbf{s}}_3,\bar{\mathbf{s}}_6\in\mathcal{C}^{N_D}} \Vert (\sum_{m=1}^{8}\sum_{n=1}^{N} \vert\bar{\mathfrak{h}}_{m,n}\vert .\hat{}2) \bullet (\vert\bar{\mathbf{s}}_3\vert .\hat{}2 + \vert\bar{\mathbf{s}}_6\vert .\hat{}2) + 2Real[\sum_{n=1}^{N}(-\bar{\mathfrak{h}}_{3,n} \bullet \bar{\mathfrak{r}}^*_{1,n} - \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{6,n} - \bar{\mathfrak{h}}_{7,n} \bullet \bar{\mathfrak{r}}^*_{5,n} + \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{r}}_{4,n} - \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{3,n} - \bar{\mathfrak{h}}^*_{6,n} \bullet \bar{\mathfrak{r}}_{8,n} - \bar{\mathfrak{h}}^*_{5,n} \bullet \bar{\mathfrak{r}}_{7,n} + \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{r}}^*_{2,n}) \bullet \bar{\mathbf{s}}_3] + 2Real[\sum_{n=1}^{N}(\bar{\mathfrak{h}}_{3,n} \bullet \bar{\mathfrak{r}}^*_{5,n} - \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{r}}_{8,n} - \bar{\mathfrak{h}}_{8,n} \bullet \bar{\mathfrak{r}}^*_{2,n} - \bar{\mathfrak{h}}_{7,n} \bullet \bar{\mathfrak{r}}^*_{1,n} + \bar{\mathfrak{h}}^*_{5,n} \bullet \bar{\mathfrak{r}}_{3,n} - \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{r}}_{7,n} - \bar{\mathfrak{h}}^*_{6,n} \bullet \bar{\mathfrak{r}}_{4,n} - \bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{r}}^*_{6,n}) \bullet \bar{\mathbf{s}}_6] + 2Real[\sum_{n=1}^{N}(-\bar{\mathfrak{h}}_{4,n} \bullet \bar{\mathfrak{h}}^*_{8,n} - \bar{\mathfrak{h}}^*_{3,n} \bullet \bar{\mathfrak{h}}_{7,n} + \bar{\mathfrak{h}}^*_{4,n} \bullet \bar{\mathfrak{h}}_{8,n} + \bar{\mathfrak{h}}_{3,n} \bullet \bar{\mathfrak{h}}^*_{7,n} - \bar{\mathfrak{h}}^*_{1,n} \bullet \bar{\mathfrak{h}}_{5,n} - \bar{\mathfrak{h}}^*_{2,n} \bullet \bar{\mathfrak{h}}_{6,n} + \bar{\mathfrak{h}}_{1,n} \bullet \bar{\mathfrak{h}}^*_{5} + \bar{\mathfrak{h}}_{2,n} \bullet \bar{\mathfrak{h}}^*_{6,n}) \bullet \bar{\mathbf{s}}_3 \bullet \bar{\mathbf{s}}^*_6] \Vert_F^2$

It can be realized that the columns ν_i, for $i = 1, \dots 8$, of S_{8b} are orthogonal, except for the pairs $\langle \nu_1, \nu_5 \rangle$, $\langle \nu_2, \nu_6 \rangle$ and $\langle \nu_3, \nu_7 \rangle$. Clearly, the orthogonality of S_{8b} (thus the diversity) is partially released to achieve the higher rate.

We now derive the maximum likelihood (ML) decoding metrics for QOSTFCs. Let us consider the two codes S_{8a} and S_{8b} as examples. Because $\mathbf{S}$ is completely orthogonal (for S_{8a}) or partially orthogonal (for S_{8b}), each MB-OFDM symbol can be decoded separately for the code S_{8a}, while a pair of MB-OFDM symbols must be decoded at a time for the code S_{8b}. The decoding metrics of MB-OFDM symbols in the two codes can be easily found based on the decoding metrics of the respective OSTBC and QOSTBC. Furthermore, each data point among $N_D = 100$ data sub-carriers (tones) within a MB-OFDM symbol $\bar{\mathbf{s}}_{t,m}$ (a pair of data points for QOSTFCs) can also be decoded separately, rather than the whole N_D data in a MB-OFDM symbol $\bar{\mathbf{s}}_{t,m}$ are decoded simultaneously. Thus the decoding process is relatively simple.

We consider a MIMO system with N Rx antennas using a PSK or QAM modulation scheme. The decoding metrics of the MB-OFDM symbols are presented in Tables II and III. From Table II (III, respectively), the data at each tone (a pair of data at each tone) can be decoded separately, rather than jointly. For instance, the decoding metric for a pair of data at the k-th sub-carrier, $k = 1, \dots, N_D$, within the MB-OFDM

TABLE IV
SIMULATION PARAMETERS.

Parameter	Value
FFT and IFFT size	$N_{fft} = 128$
Data rate	480 Mbps
Convolutional encoder's rate	1/2
Convolutional encoder's constraint length	$K = 7$
Convolutional decoder	Viterbi
Decoding mode	Hard
Number of transmitted MB-OFDM symbols	1800
Modulation	8PSK, 16QAM and 64QAM
IEEE Channel model	CM1, 2, 3 & 4
Number of data subcarriers	$N_D = 100$
Number of pilot subcarriers	$N_P = 12$
Number of guard subcarriers	$N_G = 10$
Total number of subcarriers used	$N_T = 122$
Number of samples in ZPS	$N_{ZPS} = 37$
Total number of samples/symbol	$N_{SYM} = 165$
Number of channel realizations	100

symbols $\bar{\mathbf{s}}_1$ and $\bar{\mathbf{s}}_4$ of S_{8b} in the case $N = 1$ is

$$\begin{aligned}(s_{1,k}, s_{4,k}) \quad = \quad & \arg\min_{s_1,s_4\in\mathcal{C}} \Big(\sum_{m=1}^{8} |\hbar_{m,k}|^2 \Big) (|s_1|^2 + |s_4|^2) + \\ & 2Real[(-\hbar_{6,k}^* \mathfrak{r}_{6,k} + \hbar_{4,k}\mathfrak{r}_{4,k}^* + \hbar_{3,k}^*\mathfrak{r}_{3,k} - \\ & \hbar_{2,k}^*\mathfrak{r}_{2,k} + \hbar_{8,k}\mathfrak{r}_{8,k}^* - \hbar_{1,k}\mathfrak{r}_{1,k}^* - \hbar_{5,k}\mathfrak{r}_{5,k}^* + \\ & \hbar_{7,k}^*\mathfrak{r}_{7,k})s_1] + 2Real[(\hbar_{4,k}\mathfrak{r}_{8,k}^* + \hbar_{6,k}^*\mathfrak{r}_{2,k} + \\ & \hbar_{1,k}\mathfrak{r}_{5,k}^* + \hbar_{3,k}^*\mathfrak{r}_{7,k} - \hbar_{2,k}^*\mathfrak{r}_{6,k} - \hbar_{7,k}^*\mathfrak{r}_{3,k} - \\ & \hbar_{8,k}\mathfrak{r}_{4,k}^* - \hbar_{5,k}\mathfrak{r}_{1,k}^*)s_4] + 2Real[(-\hbar_{1,k}^*\hbar_{5,k} \\ & -\hbar_{4,k}\hbar_{8,k}^* + \hbar_{4,k}^*\hbar_{8,k} - \hbar_{2,k}^*\hbar_{6,k} + \hbar_{1,k}\hbar_{5,k}^* \\ & -\hbar_{3,k}^*\hbar_{7,k} + \hbar_{2,k}\hbar_{6,k}^* + \hbar_{3,k}\hbar_{7,k}^*)s_1 s_4^*]\end{aligned}$$

where the complex space $\mathcal{C}$ denotes all potential possibilities that the PSK- or QAM-symbol s can take while the subscript n is omitted for brevity. It is clear that the decoding metric is completely linear, and thus relatively simple.

IV. SIMULATION RESULTS

In this section, we ran several Monte-Carlo simulations for the conventional MB-OFDM without STFCs, the OSTFC $\mathbf{S}_{8a}$ in (11), and the QOSTFC $\mathbf{S}_{8b}$ in (10) at the bit rate 480 Mbps for illustration. Each run of simulations was carried out with 1800 MB-OFDM symbols. One hundred channel realizations of each channel model (CM 1 to CM 4) were considered for the transmission of each MB-OFDM symbol. The simulation parameters are listed in Table IV. In simulations, SNR is defined to be the signal-to-noise ratio (dB) per sample in a MB-OFDM symbol (consisting of 165 samples), at each Rx antenna (i.e. the subtraction between the total power (dB) of the received signal corresponding to the sample of interest and the power of noise (dB) at that Rx antenna). To fairly compare the error performance of MB-OFDM systems with and without STFCs, the following two constraints are guaranteed

1) Power constraint: the average power of the signal constellation points is scaled down by a factor of 1 for the uncoded MB-OFDM, 1/4 for $\mathbf{S}_{8a}$, and 1/6 for $\mathbf{S}_{8b}$. Thereby, the *same average transmission power* from all Tx antennas at a certain time can be achieved for the three cases.
2) Data rate constraint: a suitable modulation scheme is selected for each MB-OFDM system in order to achieve the *same data rate* (8PSK for the conventional MB-OFDM, 64QAM for $\mathbf{S}_{8a}$, and 16QAM for $\mathbf{S}_{8b}$ to have the same data rate of 480 Mbps).

Figs. 2 and 3 compare the three error performances of the conventional MB-OFDM (without STFCs), $\mathbf{S}_{8a}$, and $\mathbf{S}_{8b}$. We can realize that, although only partial diversity can be achieved, the QOSTFC $\mathbf{S}_{8b}$ provides significantly better error performance, compared to the rate-1/2, full diversity OSTFC $\mathbf{S}_{8a}$, and much better error performance, compared to the conventional MB-OFDM UWB. Equivalently, the QOSTFC may provide higher data rate with the same error performance as the OSTFC.

The reasons behind the error performance advance, though $\mathbf{S}_{8b}$ possesses a smaller diversity than $\mathbf{S}_{8a}$, are due to the aforementioned constraints. The use of a higher modulation scheme for $\mathbf{S}_{8a}$ (2nd constraint) and the down-scaling of the signal constellation energy (1st constraint) cause a significant reduction in the Euclidean distance between the closest points in the signal constellation, which results in a higher BER for $\mathbf{S}_{8a}$, compared to that of $\mathbf{S}_{8b}$.

V. CONCLUSIONS

We have analyzed the application of QOSTFCs in our proposed STFC MB-OFDM UWB systems. Although only partial diversity can be achieved, QOSTFCs may still provide either a higher date rate or better error performance, compared to the full diversity OSTFC of the same order. Thus, it can be concluded that, for STFC MB-OFDM UWB, QOSTFCs might be better than OSTFCs, with the penalty of higher decoding complexity, though both have relatively simple decoding complexity.

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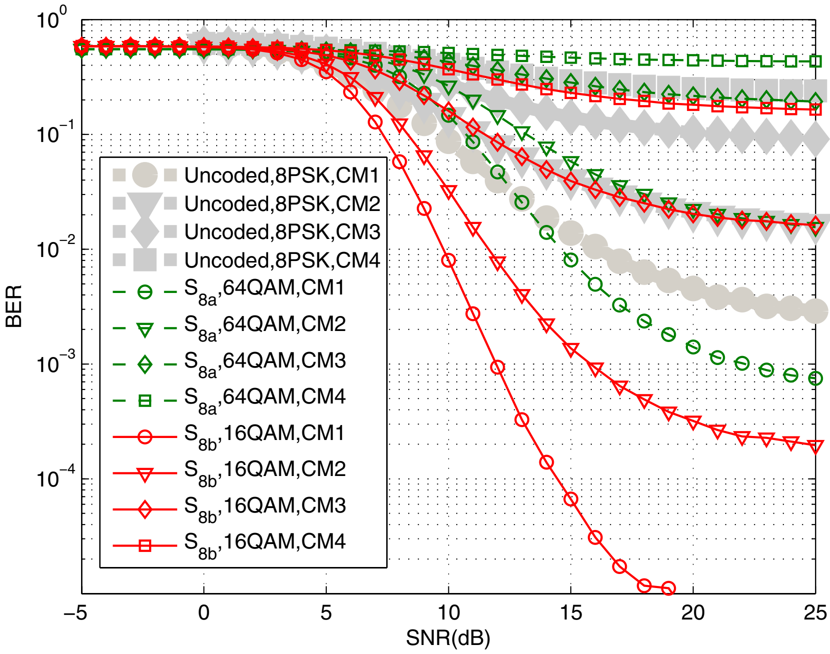

Fig. 2. STFC S_{8a} vs. QOSTFC S_{8b} with 1 Rx antennas and bit rate 480 Mbps.

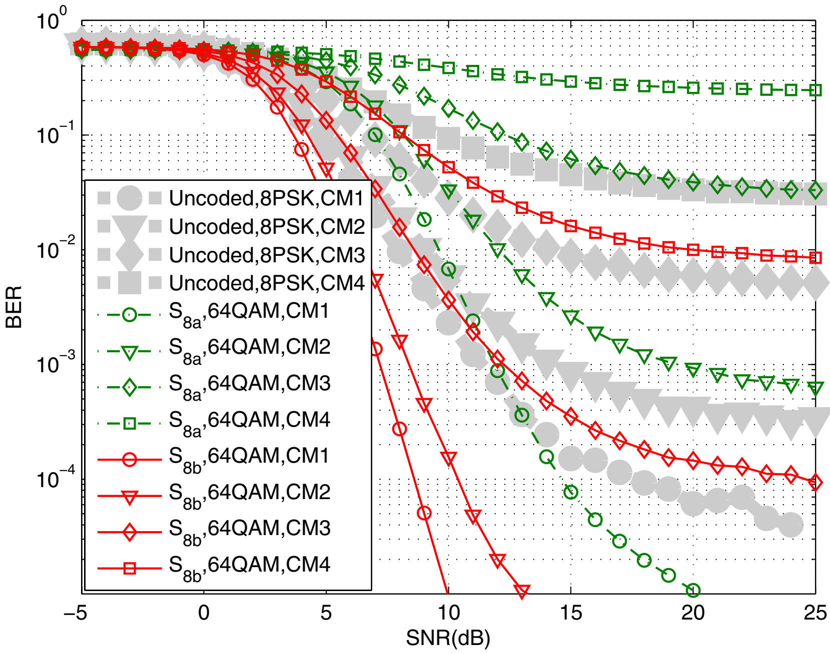

Fig. 3. STFC S_{8a} vs. QOSTFC S_{8b} with 2 Rx antennas and bit rate 480 Mbps.

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